REVIEW ARTICLE

A Review on Synthesis, Properties and Applications on Cobalt Ferrite

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ABSTRACT: Cobalt ferrite has attracted much attention owing to its excellent properties and huge technological applications. The novel synthesis methods such as co-precipitation method, solid state method, sol-gel method, auto combustion method, precursor technique, hydrothermal technique, spray pyrolysis technique etc. have been used for its preparation. Along with numerous outstanding properties of cobalt ferrite several chemical modifications like modifying reaction conditions, substituting one or more ions with other metal ions enhanced the configuration of grains of cobalt ferrite. With all the factors the role of dopant in chemical composition is extreme important because it modifies the structural, electrical, magnetic and catalytic properties of cobalt ferrite. In this review, we summarize the synthesis and properties of cobalt ferrites with significant developments. The applications of cobalt ferrite in several fields are also highlighted in this review.

KEYWORDS: Cobalt ferrite, Structural properties, Synthetic methodology, Cation distribution, Electrical and magnetic properties.

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1. INTRODUCTION

In modern days, spinel ferrites have extensively studied in the field of fundamental science and engineering. Along with remarkable properties spinel ferrites also have exceptionally promising applications such as transformer applications, telecommunications, catalysts, sensors, microwave devices, high density magnetic recording devices, biomedical applications etc [1-7]. Now a days, researchers obtained significant findings and great achievements in spinel ferrites due to their good stability, high adsorption capacities, excellent properties, optoelectronic tunability and safety, increasing their tunable applications to large extent.

In spite of several spinel ferrites, cobalt ferrite ($CoFe_2O_4$) has inverse spinel structure. In inverse spinel, the divalent ions 'A' are occupied the octahedral sites whereas half of the trivalent ions 'B' are occupied the tetrahedral sites. Ferrites are classified into "soft" and "hard" ferrites based on their magnetic properties. Soft ferrites are those have low coercivity whereas hard ferrites are those have relatively high coercivity. Due to moderate magnetization and high coercivity cobalt ferrite is considered as hard magnetic material. Along with excellent physical and chemical stability, great mechanical hardness cobalt ferrites have huge range of applications in high density disks, biomedical, photocatalysts, anti-cancer drug sensor, magnetic fluids etc. [8-12].

In addition, the distribution of various metallic ions over tetrahedral and octahedral sites may alter the electrical, structural, magnetic and catalytic properties of cobalt ferrite. The factors like charge possessed by metallic ion, its size, preparation conditions, methods preferred for synthesis affect the distribution of ions over tetrahedral and octahedral sites. Interestingly the substituted of nickel, cadmium, zinc, magnesium, aluminum and chromium [13-18] has significant effect on magnetic and dielectric properties. A large extent of work is reported on the preparation of cobalt ferrite by using several methods. The main purpose of this review is to summarize the beneficial and vast knowledge regarding the properties, synthesis and several applications of cobalt ferrite in an effective way.

2. Cobalt ferrite synthetic methods and their influence on properties

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For the synthesis of cobalt ferrite, various synthetic methods like, co-precipitation method, sol-gel method, solid state reaction, ceramic method, thermal decomposition technique, hydrothermal technique, ball milling method, flash combustion technique etc.[19-26], have been used. These fabrication techniques of cobalt ferrite are briefly explained below.

2.1. Co-precipitation Method

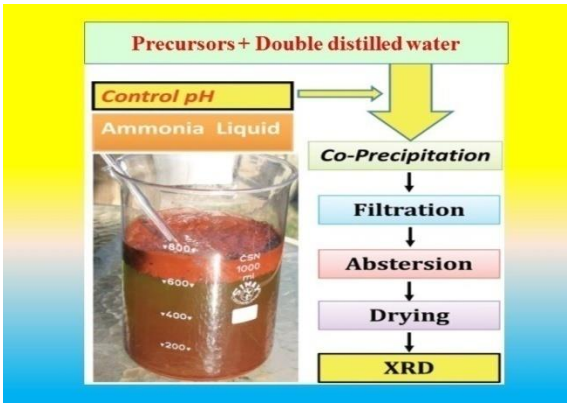

Figure 1 Schematic representation of Co-precipitation synthesis

Co-precipitation method is a simple wet chemical method widely used for the fabrication of cobalt ferrite because of its good qualities like simplicity, low cost, production of ultrafine particles and good stoichiometric control. This method involves metal salts with stoichiometric amounts dissolved in a normal solvent. Then desired pH is obtained by the addition of precipitate agent to form single phase, homogeneous inorganic solid. For prepared sample heat treatment is important for the crystallinity and growth of particles. The nucleation kinetics and growth can be adjusted by the control release of cations and anions. The particle size, shape and distribution of nano particles can be affected by the parameters like temperature, pH of desired solution, concentration of reactants and ions, kind of solution etc.

Houshiar et al., [27] prepared cobalt ferrite nanoparticles by co-precipitation method where metal chlorides as starting materials and sodium hydroxide are used as a precipitating agent. The obtained sample was heated at 600^{o}C for10h. X-ray analysis reported that the crystallite size of prepared sample is 49.5nm. VSM study showed that the saturation magnetization (M_s) of synthesized sample is 55.8 emu/g and coercivity (H_c) is 850 Oe. Surface morphology was studied by SEM and TEM images. Devi Gole et al., [28] synthesized cobalt ferrite with different pH via co-precipitation method. The XRD pattern of this study investigated that lattice parameter varied from 8.4057 to 8.3754Å for different pH and crystallite size varied in the range of 328 to 351Å.In vitro antibacterial activity reported that cobalt ferrite of pH 7 showed highest antibacterial effects and cobalt ferrite at pH 8 showed antifungal effects.

Kim et al., [29] fabricated cobalt ferrite by co-precipitation technique using chlorides are precursors and sodium hydroxide as precipitating agent. Authors reported the structural, magnetic and Mossbauer studies of obtained samples. X-ray patterns of prepared samples have taken at various temperatures. X-ray analysis revealed that the average particle size increased with increasing temperature. The morphology of samples carried out by TEM images. Mossbauer spectra presented that the superpara magnetic behavior of cobalt ferrite prepared below the lowest temperature where collective magnetic behavior exists above the highest temperature.

2.2 Sol-gel Method

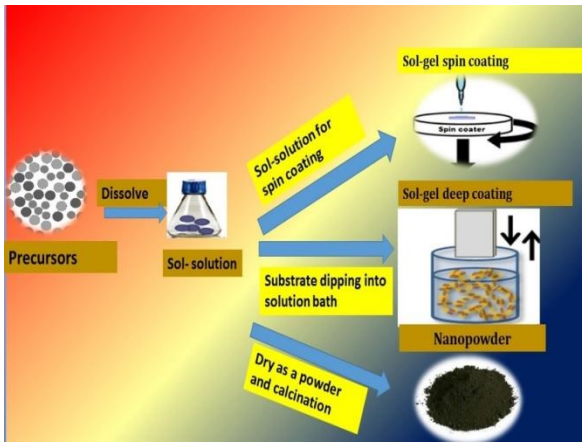

Figure 2 Schematic representation of Sol-gel method

Sol-gel method is a simple, inexpensive wet chemical method of synthesis. This method involves four important steps of preparation like hydrolysis, polycondensation, drying and thermal decomposition. In this process, the metal oxides precursors in stoichiometric amounts are dissolved in double distilled water where ethylene glycol, citric acid etc. used as a chelating agent. Gel is formed by evaporation process. This method provides the good control

on reactions include during the preparation and also provides the better control on properties of synthesized sample.

Saragi et al., [30] were achieved cobalt ferrite nanoparticles via sol-gel method. The obtained solution was refluxed at 125^{o}C for 13h and pH controlled to 9.5. The formation of cubic spinel structure and high quality crystal was confirmed by X-ray analysis. X-ray study also revealed that the crystal volume is 535.387 Å^{3} and lattice constant is 8.12 Å. From TEM images it has been reported that the particles are in oval shape with size vary from 100-200nm.The band gap 2.96 eV was obtained from Tauc plot in UV-Vis spectra.

Kanagesan et al., [31] synthesized cobalt ferrite powder via sol-gel auto combustion method in which metal nitrate solutions and citric acid solution mixed with less amount of ethylene glycol. X-ray study confirmed that the formation of inverse spinel structure cobalt ferrite nanoparticles with average size 25nm.The magnetic behavior of prepared sample was studied at room temperature by VSM characterization. Authors reported that the saturation magnetization observed maximum of 22.31 emu/g and coercivity of 118Oe.Sajja et al., [32] fabricated a series of cobalt ferrite using different complexing agents. Thermal analysis confirmed that the sample formed at 250^{o}C. From FE-SEM images the particle size found in the range between 7 and 28 nm. This study showed that the size distribution of particles and particle size affected by the different complexing agents and cross linkers. Cannas et al., [33] prepared cobalt ferrite with different concentrations dispersed in silica by using sol-gel method. This study presented that less amount of cobalt ferrite (5,10,15%) nanoparticles are spherical with narrow particle size distribution.

2.3. Solid State Reaction Method

Solid state reaction method is most widely used for the synthesis of crystalline solids. This method involves metal oxides as precursors mixed together and finely powdered using agate mortar and heated at high temperatures in muffle furnace. Solid state method requires simple apparatus and is relatively inexpensive method.

Vit et al., [34] fabricated cobalt ferrite nanoparticles using solid state reaction method. In this method solid state reaction was subjected to various chemical compositions like hematite and cobalt chloride. XRD patterns of obtained samples showed the modified individual phases. Surface morphology studied by using SEM photographs. Berbenni et al., [35] synthesized cobalt ferrite nanoparticles by solid state synthesis route. The molar heat capacity values of prepared cobalt ferrite samples at T ≥ 500 $^{\circ}$C found closer to each other while the samples prepared at 300^{o}c and 400^{o}C have lower values. Kulkarni et al., [36] employed cadmium doped cobalt zinc ferrite by simple solid state reaction method. X-ray diffraction study showed that the lattice parameter of the sample sintered at 1000^{o}Cfound to be 8.4055Å and the lattice parameter of the sample sintered at 800^{o}C found to be 8.3925^{o}C.Pandit et al., [37] prepared cobalt ferrite nanoparticles by using solid state reaction method.VSM analysis showed that the saturation magnetization of cobalt ferrite sample found to be 57.04 emu/g and coercivity of 590 Oe.

2.4. Ceramic method

Ceramic method is very simple synthetic technique requires a very high temperature for the preparation of ferrite nanoparticles. This method involves starting precursors as oxides which are mixed together and finely powdered in agate mortar. This synthesis process is followed by two steps. Firstly, the mixture is pre-calcinated at very high temperature then thermal treatment is again required for obtaining the desired sample. Rafferty et al., [38] prepared cobalt ferrite powder via solid state ceramic method in which oxides were taken as starting precursors and mixed together. The mixture was pre-calcinated at 1000^{o}C for 72h. Two steps heating were implemented. Then by evaporation process, cobalt ferrite powder was obtained. The two identical XRD patterns at 1000^{o}C and 1100^{o}C of cobalt ferrite powder reported that 100% conversion occurs to cobalt ferrite.

Mehdi et al., [39] employed pure oxides with stoichiometric amounts as starting materials and the synthetic reaction was pre-sintered at 800^{o}C for two hours then finally sintered at 1100^{o}C for five hours. X-ray analysis confirmed that the formation of single phase cubic spinel structure cobalt ferrite. Dielectric study revealed that with increase of Co content dielectric constant decrease. Tamanna et al., [40] carries out the fabrication of zinc doped cobalt ferrite via standard double sintering ceramic method. It was found that the lattice

parameters were increased with increase of zinc doping concentration. Magnetic study showed that the saturation magnetization was decreased from 13.015emu/g to 2.8575emu/g with increase of zinc content.

2.5. Thermal decomposition technique

Thermal decomposition method is an innovative way for the preparation of ferrite nanoparticles with controlled size and shape. In this method, for the production of mono dispersed ferrite nanoparticles with high quality the seed-mediated growth technique is used. Saso et al., [41] fabricated cobalt ferrite nanoparticles by three synthetic methods viz, co-precipitation from aqueous solution, co-precipitation in microemulsion and thermal decomposition method. In this work the structural and magnetic properties of corresponding samples have been studied. X-ray analysis determined the particle size of cobalt ferrite nanoparticles around 8nm. Both XRD patterns of samples prepared by co-precipitation from aqueous and by co-precipitation in microemulsion showed spinel structure of crystal while the XRD pattern of sample prepared by thermal decomposition method showed inverse spinel structure. Magnetic study revealed that the magnetic behavior of all samples strongly affected by the preparation methods.

Hyeon et al., [42] synthesized high quality and mono disperse cobalt ferrite nanoparticles by high temperature aging of metal surfactant complex by mild oxidation. X-ray study confirmed that particle size varies from 4-9 nm by changing preparation conditions.TEM analysis showed that well separation of particles with diameter of 6 nm. Xinyuan Li et al., [43] prepared well dispersed and size controlled cobalt ferrite nanocrystals by thermal decomposition method. The structural properties have been studied by XRD, XPS and FTIR spectra. HR-TEM micrograph of a single cobalt ferrite crystal showed that clear lattice fringes within whole particle. Magnetic study reported that the saturation magnetization and coercivity improves with cobalt impurities. Baaziz et al., [44] prepared spherical core-shell CoxFe1-xO@CoyFe3-yO4 nanoparticles and cobalt ferrite nanoparticles with spherical and cubic shape by using thermal decomposition method. It was found that the magnetic properties of the samples directly affected by the shape and arrangement of particles. Ibrahim et al., [45] fabricated $Co_{0.6}Zn_{0.4}Fe_2O_4$ nanoparticles by simple thermal decomposition process. XRD study reported that the formation of spinel structure with lattice parameter of 8.407Å. Spherical morphology of nanoparticles obtained from FE-SEM images. Magnetic characterizations of prepared cobalt ferrite sample showed saturation magnetization of 74.5 emu/g and coercivity of 114 Oe.

2.6. Hydrothermal technique

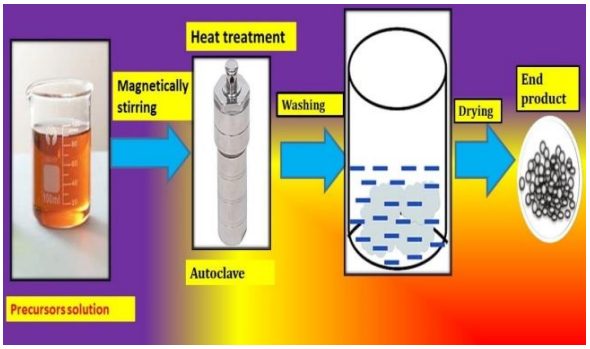

Figure 3 Schematic diagram of hydrothermal synthesis

Hydrothermal method is used for the preparation of good quality crystals with better control on their composition. In this method the crystal growth is normally performed in a high vapor pressure stainless steel autoclave. The formation of single crystal by hydrothermal route mainly depends on the solubility of metal salts in hot water under high pressure. Allaedini et al., [46] fabricated cobalt ferrite nanoparticles via hydrothermal technique in which nitrates as precursors and NaOH is used as a precipitating agent. The hydrothermal reaction was carried out in autoclave. The desired sample was obtained after calcination at 500°C for four hours. XRD and SEM analysis presented that the formation of single phase cubic crystallography with spherical shape. Magnetic properties reported that the super paramagnetic nature of cobalt ferrite. Millot et al., [47] carried out the synthesis of homogeneous and well dispersed cobalt ferrite nanopowder by two methods viz, hydrothermal and co-precipitation synthesis. In co-precipitation synthesis, cobalt ferrite powder was obtained at sintering temp 650°C. The X-ray analysis confirmed that the formation of spinel structure where SEM images determined grain size of 27nm.Zhao et al., [48] were prepared cobalt ferrite nanopowders and Fe-Co/$CoFe_2O_4$

nanocomposite by hydrothermal synthesis. The structural properties of prepared samples were studied by XRD, SEM, FT-IR characterizations. The degradation of the sample was carried out by thermogravimetric analysis.

2.7. Ball milling method

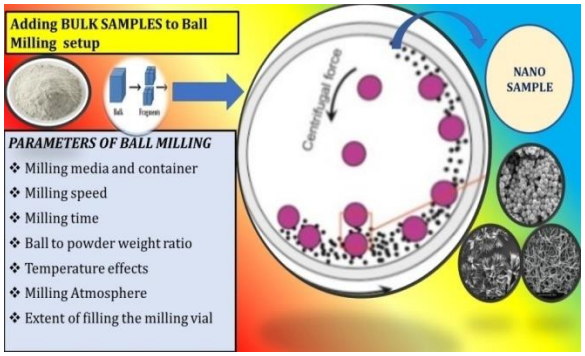

Figure 4 Schematic representation of Ball milling method

Ball milling is a mechanical process in which sample powder crushed into fine nanosized particles (shown in Fig.4). In the last decade, ball milling technique widely used for synthesis process because of its low cost, simplicity, environment friendliness as well as ability to achieve high yields. For ferrite applications such as actuators, sensors, magnetostrictive materials are considered. Magnetostrictive is a material property causes; the material possesses changes in its dimensions or shape in an external applied magnetic field. This method involves the ball milling of ferrite particles in a particular ball milling apparatus. Mahdikhah et al., [49] synthesized cobalt ferrite powder by post calcination after ball milling process. Rietveld refinement XRD data of prepared samples confirmed the formation of single phase spinel structure of ferrite. This work reported that the variation in saturation magnetization occurs with increase of Co content and decrease in particle size. Turtelli et al., [50] prepared cobalt ferrite nanoparticles by using ball milling and sol-gel method. Saturation magnetization of cobalt ferrite prepared by ball milling method found to be less than that of prepared by sol-gel method. XANES spectra exhibited that the distribution of Fe^{3+} and Co^{2+} ions depends on the preparation methodology.

2.8. Flash combustion technique

Flash combustion method is a simple, low-cost and effective synthesis method normally based on oxidation of sample by flash combustion followed by the conversion of organic and inorganic substances to combustion gases. This method involves nitrates as precursors with stoichiometric amounts and citric acid, glycine etc. used as fuel. Hathout et al., [51] fabricated cobalt ferrite nanoparticles via flash combustion synthesis route. This method involves nitrates as precursors and glycine with appropriate molar ratio mixed together. The mixture was heated on hot plate at 300^{0}C for five minutes. The combustion reaction was carried out at lowest temperature where more vapors not be produced. XRD study confirmed that the formation of spinel structure with average crystallite size of 40 nm. Spongy and fragile morphology showed by SEM micrographs. In present work, antimicrobial properties against gram positive and negative bacteria have been studied. Prabhakaran et al., [52] used combustion route for preparing highly crystalline cobalt ferrite nanoparticles, in which nitrates were used as starting materials and DL-alanine used as a fuel. The higher values of saturation magnetization (71.1emu/g) and coercivity (1100Oe) obtained for the sample calcinated at 500^{o}C /2hr.Henaish et al., [53] synthesized a series of $Co_{1-x}Mn_xFe_2O_4$ by using flash auto-combustion method. TEM study investigated that the average particle size increased from 30 nm to 100nm.The saturation magnetization of pure cobalt ferrite found to be 67.14 emu/g.

Figure 5 Schematic diagram of Synthesis methods of Cobalt ferrite

3. Influence of substituent on properties of cobalt ferrite

The substitution of various metal ions to substrate is an excellent way to enhance the magnetic, structural, biological and electrical properties. Cobalt ferrite has a great ability to incorporate several metal ions into it. The substituted cobalt ferrite properties are mainly based on site preference energy for ion, type of dopant and cation distribution. The different metal ions substitution on cobalt ferrite is explained below.

3.1. Ni Substitution

Hashim et al., [54] demonstrated, by synthesizing nanocrystalline Ni doped cobalt ferrite by sol-gel auto combustion technique. X-ray diffraction patterns of prepared compositions showed that the formation of cubic spinel structure ferrite with phase purity. The average crystallite size decreased from 43 to 22 nm with increase of Ni content. Spherical morphology showed by FE-SEM photographs. Magnetic study revealed that the saturation magnetization decreases with increase of Ni content. Mossbauer spectra measurements reported that the hyperfine magnetic field decreases at both sub-lattices with increase of Ni content. Velhal et al., [55] fabricated Ni substituted cobalt ferrite by simple auto combustion route. XRD study revealed that cubic phase spinel structure formation with average crystallite size varied from 30-44 nm. The Agglomeration and porosity of the sample studied by Scanning Electron Microscopy (SEM) images. The dielectric study reported that AC conductivity increased with frequency where dielectric constant and loss tangent decreased with frequency. Saturation magnetization with high value of 92.87 emu/gm occurred for maximum Ni content (0.4) composition. Kolekar et al., [56] prepared $Co_{0.8-x}Ni_xZn_{0.2}Fe_2O_4$ ferrite by using solid state reaction. Magnetocrystalline anisotropy increased with increase of Ni content and coercivity also increased with increase of Ni content. SEM photographs showed slightly agglomerated bead or octahedral shaped grains with clear boundaries between neighboring crystals.

3.2. Cd Substitution

Jadhav et al., [57] prepared cadmium substitutes cobalt ferrite thin films via spray pyrolysis method. They investigated that single phase cubic spinel structure with crystallite size 11-15 nm. There was a linear increase in lattice constant with increase in Cd^{2+} concentration because the larger size of guest metal ions. FT-IR spectroscopy detected that the stretching vibration band s occurred within the range 600–550 cm^{-1} at tetrahedral site and 450–385 cm^{-1} at the octahedral site. Magnetic properties investigated that the saturation magnetization, coercivity and remanence decreased with increase of Cd^{2+}content. The Cd^{2+} substitution greatly influenced the morphological, structural and magneto-optical performance of cobalt ferrite thin films. Kulkarni et al., [58] fabricated $Co_{0.5}Zn_{0.5}Cd_{1.5-x}Fe_{2-x}O_4$ ferrite samples using solid state method. The thermal analysis showed that the reaction completion temperature at around 730^oC and the reaction is endothermic in nature. SEM study revealed that tetrahedron, octahedron and granular shaped grains were formed. FT-IR peaks shifted towards lower wave number region with increase in cadmium doping content. Similarly, Singhal et al,. [59] Synthesized magnetic $CoCd_xFe_{2-x}O_4$ (x = 0·0, 0·2, 0·4, 0·6, 0·8 and 1·0) ferrite nanoparticles by sol-gel auto combustion method. The authors reported that the lattice parameter of Cd substituted cobalt ferrite higher than that of pure cobalt ferrite. It was observed that at different annealing temperatures lattice parameter remains nearly same. The D.C electrical resistivity decreased with increase of drift mobility. The positive value of See beck coefficient confirmed the *p*-type semiconducting nature. Kulkarni et al., [60] fabricated cadmium doped Co-Ni nano ferrite via co-precipitation method. XRD study investigated that lattice parameter decreased with increase of Cd content. The spinel structure of cobalt ferrite confirmed by FT-IR bands obtained for tetrahedral and octahedral vibrations. Flower structure morphology showed by SEM images.

3.3. Zn Substitution

Somaiah et al., [61] fabricated Zn substituted cobalt ferrite by auto combustion method. They investigated that the formation of cubic spinel structure ferrite samples with irregular morphology. Magnetic study revealed that the saturation magnetization varied within the range of 81.2-86.6 emu/g with coercivity 539 Oe occurred for pure cobalt ferrite. Suryanarayana et al., [62] prepared zinc doped cobalt ferrite nanoparticles via simple chemical coprecipitation synthesis. The results of VSM study showed that the saturation magnetization linearly decreased from 57.06 to 11.40 emu/g by increasing of Zn concentration. The value of

coercivity also decreased with increase of Zn content. Moreover, Sagayaraj et al., [63] synthesized zinc doped cobalt ferrite by co-precipitation method. This work reported that the XRD peaks matched with standard JCPDS: 22-1086. XRD study also confirmed that the formation of single phase cubic spinel structure with crystallite size decreased from 31 to 28 nm. SEM micrographs showed spongy morphology with agglomerated ferrite samples. TGA/DSC curves presented that there was no further decomposition of sample at 1111^{o}C.

3.4. Mg Substitution

Mund et al., [64] prepared Mg substituted cobalt ferrite by sol-gel auto combustion method. They studied the structural properties by XRD, FTIR characterizations and magnetic properties by VSM data. X-ray analysis presented that the formation of single phase cubic spinel structure while rietveld refinement confirmed the formation of cubic structure with space group *Fd3m.* FT-IR spectra revealed that the high frequency band found in the range of 580-568 cm^{-1} and low frequency band found within 424-409 cm^{-1}.VSM study reported that the saturation magnetization and magnetic moment decreased with increase of Mg content. Vemuri et al., [65] synthesized Mg doped cobalt ferrite nano particles. The lattice parameter of pure cobalt ferrite found to be 8.3845Å while that of Co0.76Mg0.24Fe2O4 ferrite was found to be 8.3702Å. Saturation magnetization obtained highest for pure cobalt ferrite sample. Raman spectra showed that highest and broader peaks observed for x=0.16 concentration of magnesium.

3.5. Al Substitution

Ali et al., [66] synthesized aluminum doped cobalt nanoferrite by citrate-nitrate auto-combustion method. Single phase spinel structure formation with crystallite size varied from 5nm to 37nm showed by X-ray study. Authors reported that saturation magnetization increased with increase of crystallite size of sample. Priya et al., [67] prepared Al doped cobalt ferrite, $Co_{1-x}\ Al_xFe_2O_4$ (x = 0, 0.1, 0.3 and 0.5) by sol-gel method. The crystallite size decreased with increase in Al content. FESEM study revealed that agglomeration found in prepared samples. Cole-Cole plot explained the prepared Al doped cobalt ferrite samples suitable for magnetic memory devices and high frequency applications. Butembu et al., [68] used sol-gel method for preparing Al doped zinc cobalt ferrite nanoparticles. Spinel structure formation was confirmed by XRD analysis. The lattice parameter decreased from 2.1157 to 2.1148Å with increase of aluminum concentration. SKPM images showed the work function of the samples found in the range of 300-680 meV. The hole density was maintained making the cobalt ferrite is a better material for applications in recording, transmission, storage and memory devices. Riyana et al., [69] successfully synthesized aluminum doped cobalt ferrite for different calcination temperatures (400^{o}C, 500^{o}C, 600^{o}C and 700^{o}C) via co-precipitation method. The crystallite size and also lattice parameter of prepared samples increased with increase of calcination temperature. Fourier transform confirmed the absorption peak of octahedral site occurred at 572.18–584.72/cm and tetrahedral site at around 374.47-424.62/cm.

3.6. Cr Substitution

Javed Iqbal et al., [70] fabricated chromium doped cobalt nanoferrites by microemulsion synthesis. The lattice parameter decreased with increase in Cr content because smaller ionic radius of dopant Cr^{3+} as compared to Fe^{3+}. They observed that the d.c electrical resistivity decreased with increase in temperature showed the semiconducting nature of ferrite sample. The coercivity also decreased with increase in Cr^{3+} content. Zengpeng Li et al., [71] synthesized chromium substituted cobalt ferrite hollow nanotubes. X-ray analysis confirmed that formation of spinel structure with phase purity. Magnetic study indicated that the values of coercivity and remanent magnetization firstly increased then decreased with Cr concentration. Vadivel et al., [72] prepared chromium doped cobalt ferrite nanoparticles by simple co-precipitation method. The average crystallite size of prepared samples occurred in the range of 15-23 nm. Diffraction patterns confirmed that synthesized ferrite with cubic spinel structure. TEM images showed the uniform distribution of nanoparticles with less agglomeration. The saturation magnetization decreased from 69.67 to 42.71 emu/g, with increasing of Cr content. The values of dielectric constant and dielectric loss are observed higher for Cr substituted cobalt ferrite than for pure cobalt ferrite samples.

Table 1 Variation of properties of cobalt ferrite by adding dopant

Transition elements substitution			
Ferrite Material	**Dopant**	**Observed Properties**	**Ref.**
$Co_{1-x}Ti_xFe_2O_4$ (x = 0 - 0.075)	Ti	• Crystallite size and lattice parameter decreased with increase in Ti content. • Maximum coercivity of 1444Oe found for high Ti content composition	[73]
$Co_{1+x}Ti_xFe_{2-2x}O_4$ (x=0.00,0.10, 0.30, 0.50)	Ti	• SEM determined grain size in the range of 42-54 nm. • Saturation magnetization, coercivity and remanence magnetization decreased with increase in Ti^{4+}content.	[74]
$CoFe_{2-x}Sc_xO_4$ (x≤1)	Sc	• Lattice parameter found as 0.8390 nm for x=0 composition. • Prepared samples showed ferromagnetic behavior.	[75]
$Co_{1-x}Cr_xFe_2O_4$	Cr	• XRD data showed that lattice parameters varied from 8.328 nm to-8.412nm. • Saturation magnetization of Cr doped cobalt ferrite was smaller than pure Co-ferrite.	[76]
$Ni_xCo_{1-x}Fe_2O_4$ (x= 0.0, 0.2, 0.4, 0.6, 0.8, 1.0)	Ni	• Spherical particles morphology observed with single phase cubic spinel structure. • BET analysis showed highest surface area154.02 m^2 g-1 observed for $Ni_{0.6}Co_{0.4}Fe_2O_4$.	[77]
$CoMn_xFe_{2-x}O_4$ with (0≤ x ≤0.6)	Mn	• Magnetic anisotropy of Mn doped cobalt ferrite increased with decrease of temperature and decreased with increase of Mn concentration. • Experimental values of saturation magnetization were found to be nearly same as the calculated maximum magnetization values at 5T.	[78]
$(Co_{1.1}Fe_{1.85}Nb_{0.05}O_4)$	Nb	• Lattice parameter of Nb doped cobalt ferrite found to be greater than that of pure cobalt ferrite. • P-E loop reported that the presence of ferroelectricity.	[79]
$CoFe_{2-x}Mo_xO_4$ (x=0.0-0.3)	Mo	• X-ray study revealed the formation of cubic phase inverse spinel structure. • Coercive field decreased with increase in Mo content.	[80]
$Y_xCoFe_{2-x}O_4$ (x= 0.2, 0.4 and 0.6)2574	Y	• Crystallite size increased from 16 to 80nm with increase in calcination temperature. • Electrical resistivity increased with increase in Y content.	[81]
Rare earth elements substitution			
Ferrite Material	**Dopant**	**Observed Properties**	**Ref.**

$CoFe_2O_4$ and $Co_{0.5}Nd_{0.5}Fe_2O_4$	Nd	• Cobalt ferrite nanoparticles showed spherical morphology whereas nanorods morphology found in Nd doped cobalt ferrite. • Saturation magnetization found to be decreased from 78.1094emu/g to 45.7068emu/g.	[82]
$CoGd_xFe_{2-x}O_4$ (x =0.0 to 0.1)	Gd	• Permittivity and dialectic loss tangent decreased with increase in Gd concentration. • Homogeneous, spherical shaped nanoparticles formed with less agglomeration.	[83]
$CoFe_{2-x}Tb_xO_4$ (with x=0 and 0.5)2575	Tb	• VSM data reported the saturation magnetization of pure cobalt higher than that of the Tb doped cobalt ferrite. • Maximum Reflection loss found to be -39 dB at 17.3 GHz resonance frequency.	[84]
$CoSm_xFe_{2-x}O_4$ (x = 0.0,0.01, 0.03, 0.07, 0.09, and 0.1)	Sm	• Rietveld refined XRD data revealed that the formation of single phase cubic spinel structured nanoferrite. • Hyperfine magnetic field decreased with decrease in Sm content on both site.	[85]
$CoFe_{(2-x)}Er_xO_4$ ($0 \leq x \geq 0.04$)2575	Er	• Coercivity of pure cobalt ferrite found to be ~29 KA/m whereas coercivity of Er doped cobalt ferrite found to be ~60 KA/m. Lattice parameter of substituted cobalt ferrite was higher than that of pure cobalt ferrite.	[86]
$Co_{1-x}Dy_xFe_2O_4$ (x=0, 0.01, 0.03, 0.05, 0.1)	Dy	• Saturation magnetization and Curie point found to be decreased with increase in Dy content. • Average Crystallite size increased with increase in Dy concentration.	[87]
$C/CoLa_xFe_{2-x}O_4$ (with x = 0.1, 0.2, 0.3)	La	• Present study confirmed that existence of carbon shells on the surface of La doped cobalt ferrite. • XRD analysis confirmed the formation of spinel structure ferrite composites.	[88]
$CoFe_{2-x}Ho_xO$2575 (x=0.00,0.01,0.03,0.05,0.07,0.1)	Ho	• Cole-Cole plot reported that optical band gap decreased with increase in Ho content. • Lattice parameter decreased with increase in Ho concentration.	[89]

4. Cobalt ferrite Applications

4.1. Cobalt ferrite as permanent magnet

Cobalt ferrite becomes a favorable candidate for exploration as a ceramic material for developing the novel magnetic recording, magneto-optical storing media and magnetostrictive smart materials. Cobalt ferrite is a hard magnetic material with high coercivity and high Curie temperature. Because of such excellent properties, physical and chemical stability, mechanical hardness cobalt ferrite has tons of applications in various fields. The various applications of cobalt ferrites are shown in Fig.3. Guanghui et al., [90] opened a new way to synthesis the cobalt ferrite used as a permanent magnet with high coercivity. They reported that glycine to nitrate ratio, annealing temperature and Co content enhanced the magnetic properties of cobalt ferrite. Kinjal et al., [91] were prepared cobalt ferrite nanoparticles for data storage applications with high saturation magnetization of 73emu/g

found at 300K.Tahereh et al., [92] developed cobalt ferrite nanoparticles of maximum coercivity 950 Oe with high saturation magnetization 45 emu/g. They reported that magnetic properties of ferrite materials mainly based on the size and shape of nanoparticles. Sylvia et al., [93] were studied the magnetic properties of cobalt ferrite by using magneto transport measurements at nanoscale. At nanometric scale the magneto transport measurements allowed the magnetic nature of ferrite films down to single domain i.e. they offered an unique probe of single domain in ferrite films. Alberto et al.[94] prepared nanoparticles with enhanced magnetic properties based on the size and morphology of nanoferrites. They reported that the exchange bias concept occurred due to the presence of antiphase boundaries which makes the ferrites for permanent magnet applications.

4.2. Cobalt ferrite biomedicine applications

Motorzhina et al., [95] investigated a novel approach for the preparation of gold/cobalt ferrite nanocomposites. There was found a better control on morphological and structural stability after the formation of nanocomposite. The prepared gold /cobalt nanocomposites can be used as multifunctional agent in hyperthermia theranostics of leukemia and in photothermal therapy. Venugopalan et al., [96] investigated cobalt ferrite nanoparticles in biological environment. The magnetic properties retain by 'nanovoyager' in different magnetic fluids like human blood hence motion in blood cells controlled magnetically over large extended periods. Mushtaq et al., [97] prepared 28nm sized, highly coercive magnetic natured cobalt ferrite nanoparticles. There was found that antibacterial potential showed the capability to develop interactions with DNA based nitrogenous. The materials prepared by surfactant based method have huge applications in the biomedical field. Sumithra et al., [98] developed cobalt ferrite nanoparticles for biomedical applications. Cobalt ferrite nanoparticles were studied for specific DNA biosensing. The antibody conjugated gold functionalized cobalt ferrite involved in sandwich type immunosensor for the detection of NT-pro BNP. For the electrochemical detection of PAR, modified glassy carbon electrode (LNT–CFO/GCE) including cobalt ferrite was designed. Amiri et al., [99] reported excellent biomedical applications of cobalt ferrite nanoparticles. The authors reported that Cobalt ferrite nanoparticles with high magnetic anisotropy used for hyperthermia applications, give controlled and effective heat generation. Authors investigated that in magnetic resonance imaging cobalt ferrite particles provide improved MR contrast and allowing smaller particle core. For isolation and genomic DNA, cobalt ferrite nanoparticles were found to be more suitable. Biosensors employed magnetic nanoparticles with different instrumentations and sensing principals. Authors reported that cobalt ferrite is good candidate in such biosensing area.

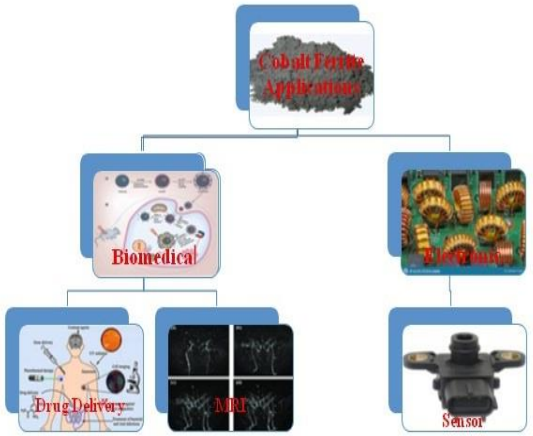

Figure 6 Cobalt ferrite applications in various fields

4.3. Cobalt ferrite in different fields

The magnetic ferrite materials are considered to be most promising electrochemical and gas sensing materials due to their electronic structure and temperature dependent surface morphology respectively. Paul et al., [100] employed cobalt ferrite nanocomposite by sol-gel auto combustion method. The combination of cobalt ferrite and IDC structure provided a good gas sensor with dynamic range, high sensitivity and selectivity for ethanol gas at low gas concentration of 7 ppm. The sensor response time found to be 180. Siavash et al., [101] employed aryl aminotetrazole and 5-aryloxytetrazoles by the treatment of cyanamides or cyanates with sodium azide in presence of cobalt ferrite as a magnetically recoverable and reusable catalyst. Researchers also have great interest in the field of composites of cobalt ferrite with graphene. The graphene sheets provide large surface area allowing interesting modifications in cobalt ferrite properties. For example, Ravi et al., [102] prepared cobalt and nickel ferrite based

graphene nanocomposites via a solvothermal process and studied their activity in acidic electrolyte. The authors reported that cobalt and nickel ferrite based graphene nanocomposite is a best electrocatalyst for hydrogen production.

5. CONCLUSION

Although a huge work was done on synthesis, applications and structural, physical, electrical, magnetic properties of cobalt ferrites the interest in this field ever increasing. Cobalt ferrite synthesis techniques enhanced their morphology, size, shape and properties. Throughout the entire discussion, the work on substituted cobalt ferrite was done on large scale. The dopant substitution also developed the properties of ferrite nanoparticles. Along with synthesis methods and substituent, cobalt ferrite applications are the most important topic. Several researchers reported the various application of cobalt ferrite in several fields. We have already discussed cobalt ferrite used in different sectors because of its excellent properties and remarkable synthetic techniques.

REFERENCES

[1] Praveena,K., Sadhana,K., Bharadwaj,S., Murthy,S.R.,2009. Development of nanocrystalline Mn-Zn ferrites for high frequency transformer applications. Magnetism and Magnetic Materials, 321, 2433-2437.

[2] Giri,J., Pradhan,P., Somani,V., Chelawat,H., Chhatre,S., Banerjee,R., Bahadur,D., 2008. Synthesis and characterizations of water-based ferrofluids of substituted ferrites [$Fe_{1-x}B_xFe_2O_4$, B=Mn, Co (x=0–1)] for biomedical applications. Magnetism and Magnetic Materials, 320, 724-730.

[3] Fernando,F.,Fernández-Saavedra,R.,BelénGómezMancebo,M.,Alfonso,V.,Miguel, S.M.,Isabel Rucandio, M.,Quejido,A.J., Romero,M., 2009. Solar hydrogen production by two-step thermochemical cycles: Evaluation of the activity of commercial ferrites. Hydrogen Energy, 34, 2918-2924.

[4] Kaneko,H., Yokoyama,T., Fuse,A., Ishihara,H., Hasegawa,N., Tamaura,Y., 2006. Synthesis of new ferrite, Al–Cu ferrite, and its oxygen deficiency for solar H2 generation from H2O. Hydrogen Energy,31, 2256 – 2265.

[5] Salunkhe,A.B., Khot,V.M., Thorat,N.D., Phadatare,M.R., Sathish,C.I. Dhawale, D.S., Pawar,S.H., 2013. Polyvinyl alcohol functionalized cobalt ferrite nanoparticles for biomedical applications, Applied Surface Science, 264, 598-604.

[6] Bhosale,R., Shende,R.V., Puszynski,J.A., 2012.Thermochemical water-splitting for H_2 generation using sol-gel derived Mn-ferrite in a packed bed reactor. Hydrogen Energy,37, 2924-2934.

[7] Tuyet Nhung,P., Tran Quang,H., and Anh-Tuan,L., 2020. Spinel ferrite (AFe_2O_4)-based heterostructured designs for lithium-ion battery, environmental monitoring, and biomedical applications.RSC Adv.10, 31622-31661.

[8] Hosni,N., Zehani,K., Bartoli,T., Bessais,L., Maghraoui-Meherzi, H., 2017. Semi-hard magnetic properties of nanoparticles of cobalt ferrite synthesized by the co-precipitation process. Alloys and Compounds,694, 1295-1301.

[9] Anastasiia,S.,G., Alexey,A.N.,Tatiana,O.A., Alevtina,S.S., Alexandra,O.P., Victor, A.N., Alexander, S.E., Peter,V.G., Alexander, G.M., Maxim, A.A., Ulf,W., 2022. Cobalt Ferrite Nanoparticles for Tumor Therapy: Effective Heating versus Possible Toxicity. Nanomaterials,12,38.

[10] Naseem,A., Nida,R., Natasha,S., Suryyia,S., Muhammad,I.K., Javier,F.G., Isaias,B.A., Muhammad,T., Zeeshan,A. and Ghazala,Y., 2020. Aluminum-Doped Cobalt Ferrite as an Efficient Photocatalyst for the Abatement of Methylene Blue. Water,12, 2285.

[11] Swathi,S., Yuvakkumar,R., Senthil Kumar,P., Ravi,G., Velauthapillai, D., 2021. Annealing temperature effect on cobalt ferrite nanoparticles for photocatalytic degradation. Chemosphere, 281,130903.

[12] Kooti, M., Afshari,M., 2012. Magnetic cobalt ferrite nanoparticles as an efficient catalyst for oxidation of alkenes. Scientia Iranica,19, 1991-1995.

[13] Joshi,S., Kamble,V.B., Kumar,M., Umarji,A.M., Srivastava,G., 2016. Nickel substitution induced effects on gas sensing properties of cobalt ferrite

nanoparticles. Alloys and Compounds, 654, 460-466.

[14] Wahsh,M.M.S.,Othman,A.G.M.,Awad,Kamal,R.,Girgis,E., Mabrouk,M.R., Morsy, Fatma,A., 2019. Synthesis and magneto-optical properties of cobalt ferrite/silica nanoparticles doped with Cd^{2+} ions. Main Group Chemistry, 18, 397-410.

[15] Praveena,K., Sadhana,K., Bharadwaj,S., Murthy,S.R.,2009. Development of nanocrystalline Mn-Zn ferrites for high frequency transformer applications. Magnetism and Magnetic Materials, 321, 2433-2437.

[16] Giri,J., Pradhan,P., Somani,V., Chelawat,H., Chhatre,S., Banerjee,R., Bahadur,D., 2008. Synthesis and characterizations of water-based ferrofluids of substituted ferrites [$Fe_{1-x}B_xFe_2O_4$, B=Mn, Co (x=0–1)] for biomedical applications.Magnetism and Magnetic Materials, 320, 724-730.

[17] Fernando,F., Fernández-Saavedra,R., Belén Gómez-Mancebo,M., Alfonso,V., Miguel, S.M., Isabel Rucandio, M.,Quejido,A.J., Romero,M., 2009. Solar hydrogen production by two-step thermochemical cycles: Evaluation of the activity of commercial ferrites.Hydrogen Energy, 34, 2918-2924.

[18] Kaneko,H., Yokoyama,T., Fuse,A., Ishihara,H., Hasegawa,N., Tamaura,Y., 2006. Synthesis of new ferrite, Al–Cu ferrite, and its oxygen deficiency for solar H2 generation from H2O. Hydrogen Energy,31, 2256 – 2265.

[19] Salunkhe,A.B., Khot,V.M., Thorat,N.D., Phadatare, M.R., Sathish,C.I., Dhawale, D.S.,Pawar,S.H.,2013. Polyvinyl alcohol functionalized cobalt ferrite nanoparticles for biomedical applications, Applied Surface Science, 264, 598-604.

[20] Bhosale,R., Shende,R.V., Puszynski,J.A., 2012.Thermochemical water-splitting for H_2 generation using sol-gel derived Mn-ferrite in a packed bed reactor. Hydrogen Energy, 37, 2924-2934.

[21] Tuyet Nhung,P., Tran Quang,H., and Anh-Tuan,L., 2020. Spinel ferrite (AFe_2O_4)-based heterostructured designs for lithium-ion battery, environmental monitoring, and biomedical applications. RSC Adv.10**,** 31622-31661.

[22] Hosni,N., Zehani,K., Bartoli,T.,Bessais,L., Maghraoui-Meherzi, H.,2017. Semi-hard magnetic properties of nanoparticles of cobalt ferrite synthesized by the co-precipitation process.Alloys and Compounds,694, 1295-1301.

[23] Anastasiia,S.,G., Alexey,A.N.,Tatiana,O.A., Alevtina,S.S., Alexandra, O.P., Victor, A.N., Alexander, S.E., Peter, V.G., Alexander, G.M., Maxim, A.A., Ulf, W., 2022. Cobalt Ferrite Nanoparticles for Tumor Therapy: Effective Heating versus Possible Toxicity. Nanomaterials*,*12,38.

[24] Naseem,A., Nida,R., Natasha,S., Suryyia,S., Muhammad,I.K., Javier,F.G., Isaias,B.A., Muhammad,T., Zeeshan,A. and Ghazala,Y., 2020. Aluminum-Doped Cobalt Ferrite as an Efficient Photocatalyst for the Abatement of Methylene Blue. Water,12, 2285.

[25] Swathi,S., Yuvakkumar,R., SenthilKumar, P., Ravi,G., Velauthapillai, D., 2021. Annealing temperature effect on cobalt ferrite nanoparticles for photocatalytic degradation. Chemosphere, 281,130903.

[26] Kooti, M., Afshari,M., 2012. Magnetic cobalt ferrite nanoparticles as an efficient catalyst for oxidation of alkenes.Scientia Iranica,19, 1991-1995.

[27] Joshi,S.,Kamble,V.B., Kumar,M.,Umarji,A.M.,Srivastava,G., 2016. Nickel substitution induced effects on gas sensing properties of cobalt ferrite nanoparticles.Alloys and Compounds, 654, 460-466.

[28] Wahsh,M.M.S.,Othman,A.G.M.,Awad,Kamal,R.,Girgis,E.,Mabrouk,M.R.,Morsy,Fatma,A., 2019.Synthesis and magneto-optical properties of cobalt ferrite/silica nanoparticles doped with Cd^{2+} ions. Main Group Chemistry, 18, 397-410.

[29] Anu,K.,Hemalatha,J., 2019. Magnetic and electrical conductivity studies of zinc doped cobalt ferrite nanofluids. Molecular Liquids,284, 445-453.

[30] Chahar, D., Thakur,P., Kumar,R., Thakur,A., 2022.Influence of Mg doping on the structural, electrical and dielectric properties of Co-Zn nanoferrites. Magnetism and Magnetic Materials,544,168726.

[31] Abbas,N., Rubab,N., Sadiq,N.,Manzoor,S., Khan,M.I.,Garcia,J.F., Aragao.I.B.,Tari,M., Akhtar,Z., Yasmin,G., 2020.Aluminum-

Doped Cobalt Ferrite as an Efficient Photocatalyst for the Abatement of Methylene Blue. Water,12,2285.

[32] Zeehan,T., Anjum,S., Waseem,S., Riaz,M., Zia,R.,2019. Tuning of Structural, Magnetic and Optical Properties of Silver Doped Cobalt Chromium Ferrite Ferrites Thin Film by Pld Technique. Nanomaterials and Biostructures, 14, 855-866

[33] Surendra,M.K., Kannan,D., Rao.M.S.R., 2011. Magnetic and dielectric properties study of cobalt ferrite nanoparticles synthesized by co-precipitation method. MRS Proceedings,1368,11-40.

[34] Toksha,B.G., Shirsath,S.E., Patange,S.M., Jadhav,K.M.,2008.Structural investigations and magnetic properties of cobalt ferrite nanoparticles prepared by sol–gel auto combustion method. Solid State Communications,147, 479-483.

[35] Kulkarni,A.B., Mathad,S.N., 2018. Synthesis and Structural Analysis of Co–Zn–Cd Ferrite by Williamson–Hall and Size–Strain Plot Methods.Self-Propagating High-Temperature Synthesis,27,37-43.

[36] Murugesan,C.,Perumal,M.,Chandrasekaran,G., 2014. Structural, dielectric and magnetic properties of cobalt ferrite prepared using auto combustion and ceramic route. Physica B: Condensed Matter, 448,53-56.

[37] Prasad,S., Vijayalakshmi.A., Gajbhiye,N.S., 1998. Synthesis of Ultrafine Cobalt Ferrite by Thermal Decomposition of Citrate Precursor.Thermal Analysis and Calorimetry, 52, 595–607.

[38] Zalite,I., Heidemane,G., Kuznetsova,L., Maiorov,M., 2015. Hydrothermal Synthesis of Cobalt Ferrite Nanosized Powders. Materials Science and Engineering,77, 012011.

[39] Chinnasamy,C.N., Narayanasamy,A., Ponpandian,N., Joseyphus, R.J., Ferrimagnetic ordering in nanostructured $CdFe_2O_4CdFe_2O_4$ spinel. Applied Physics, 90, 527.

[40] Biasi,R.S.,Figueiredo,A.B.S.,Fernandes,A. A.R.,2007.Synthesis of cobalt ferrite nanoparticles using combustion waves. Solid State Communications, 144, 15-17.

[41] Houshiar,M., Zebhi,F., Razi,Z.J., Alidoust,A., Askari,Z.,2014.Synthesis of cobalt ferrite ($CoFe_2O_4$) nanoparticles using combustion, co-precipitation, and precipitation methods: A comparison study of size, structural, and magnetic properties. Magnetism and Magnetic Materials,371,43-48.

[42] Gole,D.B., Kapatkar,S.B., Mathad,S.N., Chavan,R.R., 2020. In Vitro Antimicrobial Activity of Cobalt Ferrite Nanoparticles Synthesized by Co-Precipitation Method. Acta Chemica Iasi, 28, 225-236.

[43] Kim,Y., Kim,D., Lee,C.S., 2003. Synthesis and characterization of $CoFe_2O_4$ magnetic nanoparticles prepared by temperature-controlled coprecipitation method. Physica B., 337,42–51.

[44] Saragi,T., Nurjannah,S., Novia,R., Syakir,N., Simanjuntak,E., Safriani,L., Risdiana and Bahtiar,A., 2015. Synthesis of Cobalt Ferrite Particles by Utilized Sol-Gel Method. Materials Science Forum, 827,219-222.

[45] Kanagesan,S.,Hashim,M., Tamilselvan,S., Alitheen,N.B., Ismail, Syazwan,M., Zuikim,M.M.M., 2013. Sol-gel auto-combustion synthesis of cobalt ferrite and its cytotoxicity properties. Nanomaterials and Biostructures, 8,1601-1610.

[46] Sajjia,M., Oubaha,M., Hasanuzzaman,M., Olabi,A.G., 2014. Developments of cobalt ferrite nanoparticles prepared by the sol–gel process. Ceramics International, 40,1147-1154.

[47] Cannas,C. ,Musinu,A., Piccaluga,G., Fiorani,D., Peddis,D., Rasmussen,H.K., Mørup. S., 2006. Magnetic properties of cobalt ferrite-silica nanocomposites prepared by a sol-gel autocombustion technique. J.Chem Phys.,125, 164714.

[48] Prochazka,V.Burvalova,A., Vrba,V., Kopp,J. and Novak,P., 2020. Formation of Cobalt Ferrites Investigated by Transmission and Emission Mössbauer Spectroscopy. Acta Chimica Slovenica, 67, 522–529.

[49] Berbenni,V., Milanese,C., Bruni,G., Girella, A., Marini, A., 2010. Mechanothermal Solid-state Synthesis of Cobalt(II) Ferrite and Determination of its Heat Capacity by MTDSC.

Zeitschrift fur Naturforschung,65,1434–1438.

[50] Kulkarni,A.B., Mathad,S.N., 2018. Effect of Sintering Temperature on Structural Properties of Cd doped Co-Zn Ferrite. Nano- And Electronic Physics, 10,01001.

[51] Pandit,R., Sharma,K.K., Kaur,P., Kumar,R.,2014.Cation distribution controlled dielectric, electrical and magnetic behavior of In^{3+} substituted cobalt ferrites synthesized via solid-state reaction technique.Materials Chemistry and Physics,148,988-999.

[52] Rafferty, Prescott,T., Brabazon,D., 2008. Sintering behavior of cobalt ferrite ceramic. Ceramics International, 34,15–21.

[53] Diwan,M.H., Bakr,N.A. and Sheini,F.J., 2014. Structural and dielectric studies of cobalt ferrite nanopowder prepared by ceramic method. Current Research, 6,4562-4566.

[54] Mariam,T., Esha,I.N., Khan,M.N.I., Choudhury,S. and Maria,K.H., 2020. Synthesis of Zinc substituted cobalt ferrites via standard double sintering ceramic technique: A study on their structural, magnetic and dielectric properties. Ceramic Processing Research, 21, 442-449.

[55] Gyergyek,S., Makovec,D., Kodre,A., Arcon,I., Jagodic,M., Drofenik,M., 2009. Influence of synthesis method on structural and magnetic properties of cobalt ferrite nanoparticles. Nanoparticle Research, 12(4),1263-1273.

[56] Hyeon,T., Chung,Y., Park,J., Lee,S.S., Kim,Y.W., Park,B.H., 2002. Synthesis of Highly Crystalline and Monodisperse Cobalt Ferrite Nanocrystals. Physical Chemistry,106,6831-6833.

[57] Li,X., Sun,Y., Zong,Y., Wei,Y., Liu,X.,Li,X.,Peng,Y., Zheng,X., 2020. Size-effect induced cation redistribution on the magnetic properties of well-dispersed $CoFe_2O_4$ nanocrystals. Alloys and Compounds, 841, 155710.

[58] Baaziz,W., Pichon,B.P., Liu,Y., Greneche,J.M., Bouillet,C.U., Terrier,E., Bergeard,N., Halte,V., Boeglin,C., Choueikani,F., Toumi,M., Mhiri,T. and Colin,S.B.,2014. Tuning of Synthesis Conditions by Thermal Decomposition toward Core–Shell $Co_xFe_{1-x}O@Co_yFe_{3-y}O_4$ and $CoFe_2O_4$ Nanoparticles with Spherical and Cubic Shapes. Chem. Mater.,26, 5063–5073.

[59] Shari,I.,Zamanian,A., Behnamghader,A., 2016.A Simple Thermal Decomposition Method for Synthesis of Co0.6Zn0.4Fe2O4 Magnetic Nanoparticles.Ultrafine Grained and Nanostructured Materials, 49, 87-91.

[60] Allaedini,G., Tasirin,S.M., Aminayi,P., 2015. Magnetic properties of cobalt ferrite synthesized by hydrothermal method,Nano Letters, 5,183–186.

[61] Millot,N., Gallet,S.L., Aymes,D., Bernard,F., Grin,Y., 2007. Spark plasma sintering of cobalt ferrite nanopowders prepared by coprecipitation and hydrothermal synthesis. European Ceramic Society, 27,921-926.

[62] Zhao,L., Zhang,H., Xing,Y., Song,S., Yu,S., Shi,W., Guo,X., Yang,J., Lei,Y., Cao,F.,2008. Studies on the magnetism of cobalt ferrite nanocrystals synthesized by hydrothermal method. Solid State Chemistry, 181, 245–252.

[63] Mahdikhah,V., Ataie,A., Babaei,A., Sheibani,S., Yang,C.W.O., Khabbaz,S., Abkenar,2019. Control of structural and magnetic characteristics of cobalt ferrite by post-calcination mechanical milling,Physics and Chemistry of Solids,134, 286-294.

[64] Turtelli,R.S., Atif,M., Mehmood,N., Kubel,F., Biernacka,K., Linert,W., Grössinger,R., Kapusta,C., Sikora,M., 2012. Interplay between the cation distribution and production methods in cobalt ferrite. Materials Chemistry and Physics, 132,832-838.

[65] Hathout,A.S., Aljawish,A., Sabry,B.A., El-Nekeety,A.A., Roby,M.H., Deraz,N.M., Aly,S.E., Abdel-Wahha,M.A., 2017. Synthesis and characterization of cobalt ferrites nanoparticles with cytotoxic and antimicrobial properties. Applied Pharmaceutical Science, 7,086-092.

[66] Prabhakaran,T., Hemalatha,J., 2016. Combustion synthesis and characterization of cobalt ferrite nanoparticles. Ceramics International,42,14113-14120.

[67] Henaish,A.M.A., Hemeda,O.M.,Alqarni,A., Refaay,D.E.E.,Mohamed,S. & Hamad,M.A .2020. The role of flash auto-combustion method and Mn doping in improving dielectric and magnetic

properties of $CoFe_2O_4$. Applied Physics A,126, 834.

[68] Hashim,M., Alimuddin, Kumar,S., Shirsat,S.E., Kotnala,R.K., Shah,J., Kumar,R., 2013. Synthesis and characterizations of Ni^{2+} substituted cobalt ferrite nanoparticles.Materials Chemistry and Physics, 139, 364-374.

[69] Velhal,N.B.,Patil,A.R., Deshpande,N.G.and Puri,V.R., 2015. Structural, dielectric and magnetic properties of nickel substituted cobalt ferrite nanoparticles: Effect of nickel concentration. AIP Advances, 5, 097166.

[70] Kolekar,R.Y., Kapatkar,S.B., Mathad,S.B., 2020. Nickel-Doped Cobalt Zinc Ferrites $Co_{0.8-x}NixZn_{0.2}Fe_2O_4$(x=0.0–0.56)by Solid-State Reaction: Synthesis and Characterization, Self-Propagating High-Temperature Synthesis, 29,196–201.

[71] Jadhav,G.L.,Khirade,P.P., Chavan,A.R., Kale C.M.& K. M. Jadhav, 2021. Structural, Optical and Magnetic Properties of Diamagnetic Cd^{2+} Incorporated Cobalt Ferrite Thin Films Deposited by Spray Pyrolysis. Electronic Materials,50,6525–6534.

[72] Kulkarni,A.B., Hegde,N.D., Gowda,S.H. and Mathad,S.N., 2020. Influence of Cadmium Substitution on Structural and Mechanical Properties of Co-Ni Nano Ferrite Synthesized by Co-Precipitation Method. Macromol. Symp.,393, 1900213.

[73] Singhal,S., Jauhar,S., Chandra,K. And Bansal,S.,2013. Spin canting phenomenon in cadmium doped cobalt ferrites, $CoCd_xFe_{2-x}O_4$ (x = 0·0, 0·2, 0·4, 0·6, 0·8 and 1·0), synthesized using sol–gel auto combustion method. Bull. Mater. Sci., 36,107–114.

[74] Kulkarni,A.B., Mathad,S.N., 2019.Variation in structural and mechanical properties of Cd-doped Co-Znferrites. Materials Science for Energy Technologies, 2,455-462.

[75] Somaiah,N., Jayaraman,T.V., Joy,P.A. and Das,D.,2012. Magnetic and magnetoelastic properties of Zn-doped cobalt-ferrites$CoFe_{2-x}Zn_xO_4$. (x = 0, 0.1, 0.2, and 0.3). Magnetism and Magnetic Materials,324,2286–2291.

[76] Suryanarayana,B., Raghavendra,V., Chandra,K., Mouli and Raghupathireddy,P.,2016. Effect of Zinc Doped in Cobalt Ferrite Nano Particles Prepared by Chemical Co-Precipitation Method. Chemical Science Transactions,5, 741-747.

[77] Sagayaraj,R., Aravazhi,S., Chandrasekaran, G., 2019. Effect of Zinc Content on Structural, Functional, Morphological, Resonance, Thermal and Magnetic Properties of $Co_{1-x}Zn_xFe_2O_4$/PVP Nanocomposites. Inorganic and Organometallic Polymers and Materials, 29,2252–2261.

[78] Mund,H.S.,Ahuja,B.L., 2016. Structural and magnetic properties of Mg doped cobalt ferrite nano particles prepared by sol-gel method. Materials Research Bulletin, 85, 228-233.

[79] Vemuri,R., Raju,G., Prasad,M.S.N.A., Rajesh,E., Pavan Kumar,G., Murali,N.,2019. Effect on structural and magnetic properties of Mg^{2+}substituted cobalt nano ferrite. Results in Physics,12, 947-952.

[80] Ali,T.M., Ismail,S.M., Mansour,S.F., Abdo,M.A., Yehia,M., 2021. Physical properties of Al-doped cobalt nanoferrite prepared by citrate-nitrate auto combustion method. Materials Science: Materials in Electronics, 32, 3092–3103.

[81] Sathiya Priya,A., Geetha,D., Kavitha,N., 2019. Effect of Al substitution on the structural, electric and impedance behavior of cobalt ferrite. Vacuum,160, 453-460.

[82] Sabastine,B., Akou,O.G., Kuria,K.P., Mwangi G.J.,Francis,N., 2020. Optical and scanning kelvin probe microscopic characterization of sol-gel synthesized aluminum doped zinc cobalt ferrite nanoparticles.PhysicalSciences,15(4),151-161.

[83] Setiyani,R.I., Utari and Purnama,B., 2020. Effect of annealing temperature on XRD and FT-IR analysis on $CoAl_{0.1}Fe_{1.9}O_4$ nanoparticles by coprecipitation. AIP Conference Proceedings, 2296, 020051.

[84] Iqbal,M.J.,Siddiquah,M.R.,2008. Electrical and magnetic properties of chromium-substituted cobalt ferrite nanomaterials. Alloys and Compounds, 453,513-518.

[85] Li,Z., Dai,J., Cheng,C.,Suo Z. and qing,W., 2020. Synthesis and magnetic properties of chromium doped cobalt

ferrite nanotube. Material Research Express,7, 086102.

[86] Vadivel,M.,Babu,R.R.,Sethuraman,K.,Ramamurthi,K.,Arivanandhan,M.,2014. Synthesis, structural, dielectric, magnetic and optical properties of Cr substituted $CoFe_2O_4$ nanoparticles by co-precipitation method.Magnetism and Magnetic Materials,362, 122-129.

[87] Amaliya,A.P.,Anand,S., Pauline,S., 2018. Investigation on Structural, Electrical and Magnetic Properties of Titanium substituted Cobalt Ferrite nanocrystallites. Magnetism and Magnetic Materials, 467,14-28.

[88] Patil,B.A., Kokate,R.D., 2018. Synthesis and Design of Magnetic Parameters by Ti doping in Cobalt Ferrite Nanoparticles for Nanoelectronics Applications. Procedia Manufacturing, 20,147-153.

[89] Lefevre,C., Roulland,F., Viart,N., Greneche,J.M., Pourroy,G., 2010. Magnetic dilution of the iron sublattice in $CoFe_{2-x}Sc_xO_4$ ($0 \le x \le 1$).Solid State Chemistry,183,2623–2630.

[90] Raju,G.,Murali,N.,Prasad,M.S.N.A.,Suresh, B.,Babu,D.A.,Kiran,M.G.,Ramakrishn,A., Wegayehu,M.T.,Babu,B,K., 2019. Effect of chromium substitution on the structural and magnetic properties of cobalt ferrite. Materials Science for Energy Technologies,2, 78-82.

[91] Singh.C.,Goyal,A., Singhal,S., 2014. Nickel-doped cobalt ferrite nanoparticles: efficient catalysts for the reduction of nitroaromatic compounds and photo-oxidative degradation of toxic dyes. Nanoscale,**6**, 7959-7970.

[92] Melikhov,Y.,SnyderJ.,E. and Jiles,D.C., Ring,A.P., Paulsen,J.A. and Lo,C.C.H., Dennis,K.W.,2006. Temperature dependence of magnetic anisotropy in Mn-substituted cobalt ferrite.Applied Physics, 99, 08R102

[93] Kiran,R.R., Mondal,R.A., Dwevedi,S.,Markandeyulu,G.,2014. Structural, magnetic and magnetoelectric properties of Nb substituted Cobalt Ferrite. Alloys and Compounds,610, 517-521.

[94] Orozco,C., Melendez,A., Manandhar,S., Singamaneni,R., Reddy,K.M., Gandha,K., Nlebedim,I. and Ramana,C.V., 2017. Effect of Molybdenum Incorporation on the Structure and Magnetic Properties of Cobalt Ferrite. Physical Chemistry, 121, 25463–25471.

[95] Shobana ,M.K., Nam,W., Choe,H., 2013. Yttrium-doped cobalt nanoferrites prepared by sol-gel combustion method and its characterization. Nanoscience and Nanotechnology,13,3535-3538.

[96] Mounkachi,O.,Lamouri,R., Abraime,B., Ez-Zahraouy,H.,Kenz,A.E., Hamedoun, M., Benyoussef, A., 2017. Exploring the magnetic and structural properties of Nd-doped Cobalt nano-ferrite for permanent magnet applications. Ceramics International,43, 14401-14404.

[97] Pervaiza E. and Gula,I.H., 2012.Structural, Electrical and Magnetic Studies of Gd^{3+}doped Cobalt Ferrite Nanoparticles. Current Engineering and Technology, 2,377-387.

[98] Tahmineh Sodaee, Ali Ghasemi, Ebrahim Paimozd, Andrea Paesano Jr., Akimitsu Morisako, 2012. The role of terbium cation substitution on the magnetic properties of cobalt ferrite nanoparticles, Journal of Magnetism and Magnetic Materials. 330.169-173.

[99] Hashim,M.,Boda,N.,Ahmed,A., Sharma,S. K., Ravinder,D.,Sumalatha,E., Ul-Hamid,A.,Ismail,M.M., Chaman,M., Shirsath,S.E.,Kumar,R.,Kumar,S.,Meena,S.S.& Nasir,M.,2021. Influence of samarium doping on structural, elastic, magnetic, dielectric, and electrical properties of nanocrystalline cobalt ferrite. Applied Physics A, 127,526.

[100] Prathapani,S.,Vinitha,M., Jayaraman,T.V. and Das,D., 2014. Effect of Er doping on the structural and magnetic properties of cobalt-ferrite. Applied Physics,115, 17A502.

[101] Karimi,Z.,Mohammadifar,Y.,Shokrollahi, H.,Khameneh, Asl,S., Yousefi,G., Karimi,L., 2014. Magnetic and structural properties of nano sized Dy-doped cobalt ferrite synthesized by co-precipitation. Magnetism and Magnetic Materials,361, 150-156.

[102] Zhou,J.,Wang,M.,Shu,X.,Ma,J.,Ren,H.,Wang,Y., Liu,Y., Shu,R.,Oh,W.C., Kong,L.B., 2020. Facile synthesis of La-doped cobalt ferrite @ glucose-based carbon composite as effective multiband microwave absorber. American Ceramic Society, 104, 2191–2200.

[103] Pessoni,H.V.S., Alves,T.E.P., Banerjee,P., Júnior,A.F., 2019.Functional properties of Ho^{3+} substituted cobalt ferrite in the context of the reduced mass model,Physica B: Condensed Matter, 575, 411676.

[104] Guanghui,H., Menggang,L., Yongsheng,Y., Weiwei,Y., Ji,L., Shichong. X., Ming,F., Haibo L., 2019. Structure and magnetic properties of cobalt ferrite foam with low mass density. Alloys and Compounds, 790,947-954.

[105] Gandha,K., Elkins,K., Poudyal, N., Liu,J.P., 2015. Synthesis and characterization of $CoFe_2O_4$ nanoparticles with high coercivity. Applied Physics,117, 17A736.

[106] Shahjuee,T., Masoudpanah,S.M., Mirkazemi, S.M. 2017. Co-precipitation Synthesis of CoFe2 O4 Nanoparticles for Hyperthermia. Ultrafine Grained and Nanostructured Materials,50,105-110.

[107] Matzen,S., Moussy,J.B., Mattana,R., Bouzehouane,K., Deranlot,C., 2012. Nanomagnetism of cobalt ferrite-based spin filters probed by spin-polarized tunneling. Applied Physics Letters, 101, 042409.

[108] López-Ortega,A., Lottini,E., Bertoni,G., Fernández,C.J. and Sangregoregorio,C., 2017. Topotaxial Phase Transformation in Cobalt Doped Iron Oxide Core/Shell Hard Magnetic Nanoparticles. Chemistry of Materials. 29, 1279–1289.

[109] Motorzhina,A., Jovanovi,S., Belyaev,V.K., Murzin,D., Pshenichnikov, S., Kolesnikova, V.G., Alexander, S., Omelyanchik, Gazvoda,L., Spreitzer,M., Panina,L., Rodionova,V., Vukomanovi,M. and Levada,K., 2021. Innovative Gold/Cobalt Ferrite Nanocomposite: Physicochemical and Cytotoxicity Properties. Processes*, 9,2264.*

[110] Lekshmy,P., Venugopalan, Sai,R., Chandorkar,Y., Basu,B., Shivashankar,S., Ghosh,A., 2014. Conformal cytocompatible ferrite coatings facilitate the realization of a nanovoyager in human blood. Nano Lett.,14,1968-1975.

[111] Mushtaq,M.W., Imran,M., Bashir,S., Kanwal,F., Mitu,L., 2016. Synthesis, structural and biological studies of cobalt ferrite nanoparticles. Bulgarian Chemical Communications, 48,565-570.

[112] Srinivasan,S.Y., Paknikar,K.M., Bodas, D.. Gajbhiye,V., 2018. Applications of cobalt ferrite nanoparticles in biomedical nanotechnology. Nanomedicine (Lond), 13, 1221-1238.

[113] Amiri,S., Shokrollahi,H., 2013. The role of cobalt ferrite magnetic nanoparticles in medical science. Materials Science and Engineering: C, 33,1-8.

[114] Paul,J., Philip,J., 2020. Inter-digital capacitive ethanol sensor coated with cobalt ferrite nano composite as gas sensing material. Materials Today: Proceedings,25,148-150.

[115] Bahari,S., Rezaei, A., 2014. $CoFe_2O_4$ Nanoparticles as a Magnetically Recoverable and Reusable Catalyst for the Synthesis of Arylaminotetrazoles and 5-aryloxytetrazoles. Chemical Research,38,65-68.

[116] Nivetha,R., Santhosh,C., Kollu,P., Jeong,S.K., Bhatnagar,A.,Grace,A.N.,2018. Cobalt and nickel ferrites based graphene nanocomposites for electrochemical hydrogen evolution. Magnetism and Magnetic Materials, 448, 165-171.